Liquefaction Potential of Silty Sand in Simple Shear

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RECEIVED ON 16.02.2012 ACCEPTED ON 18.09.2012

ABSTRACT

In this paper, the liquefaction potential of medium dense and dense sand layers was studied by performing constant volume (undrained) cyclic simple shear tests using cyclic simple shear apparatus. Strain-controlled approach was adopted. The liquefaction potential of two layers of a silty sand soil profile consisting of surface medium dense layer and underlying dense sand layers were studied. A medium dense sand surface layer exhibited flow type total liquefaction in cyclic loading in few cycles after initial liquefaction. An underlying dense sand base layer showed initial liquefaction in relatively more number of cycles and then cyclic mobility due to which pore pressure increases and decreases with cycles that is the characteristics of dense sand. The pore pressure increase and decrease is directly related to decrease and increase of effective stress.

Key Words: **Strain-Controlled, Medium Dense Sand, Dense Sand, Liquefaction, Cyclic Mobility, Shear Strength.**

1. INTRODUCTION

The buildings on shallow foundations which are constructed over liquefiable loose or medium dense sand deposits in coastal areas or where water is high, suffer significant damage due to liquefaction-induced settlements and tilting. These large settlements are caused due to, bearing capacity failure (shear failure) when the soil loses stiffness as a result of liquefaction. This behaviour of shallow foundations have been reported during earthquakes such as Niigata, Japan, [1], Dagupan City, Philippines, [2], Chi-Chi, Taiwan, [3] and Kocaeli, Turkey, [4-5].

Many researchers have carried out stress-controlled [6] and strain-controlled tests [7-8] to study the liquefaction potential of loose and medium dense sand. However, stress-controlled tests may not be suitable and strains may exceed the measured range before the stresses reach the specified amplitude for relatively loose sand subjected to higher stress amplitude. On the other hand, strain-controlled cyclic simple loading directly relate pore pressure and consequent liquefaction with the amplitude of shear strains [9]. Further, these types of tests more closely simulate the earthquake loading.

From literature review [7-8] it is evident that study on liquefaction potential of silty sand using strain-controlled cyclic simple loading is at primary stage and comprehensive data is not available in literature. Much work is still needed to better understand the liquefaction potential of silty sand.

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Therefore, to gain improved understanding of the liquefaction potential of sand considered for potential numerical models, strain-controlled constant volume cyclic simple shear tests were performed. This study will contribute to improved understanding of liquefaction of this type of material.

In this type of test the cyclic loading with controlled constant shear strain amplitude is applied and the shear stress is recorded. In liquefaction studies this approach is called the strain-approach. For all tests, the standard sinusoidal displacement wave was applied at frequency of 0.1Hz. Although this frequency is less than the characteristic frequency content of a typical earthquake, it is in the recommended frequency range for this apparatus to provide consistent results [10]. Further, the undrained behaviour of sand is known to be frequency independent [10], thus, the approach is reasonable in laboratory cyclic testing of soils.

1.1 The Soil Profile

A typical two layer soil profile was considered as shown in Fig.1. This soil profile consists of 10m thick surface liquefiable medium dense Leighton Buzzard E-Fraction silty sand (at relative density of 40%) with underlying a 10m thick non liquefiable dense layer of the same sand (at a higher relative density of 80%). Further details have been described in Almani, [11].

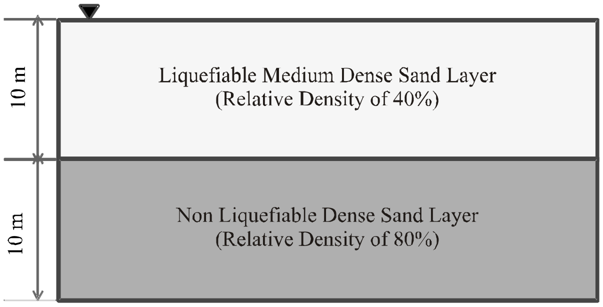

FIG. 1. THE SOIL PROFILE

2. TESTING APPARATUS

The simple shear, triaxial compression and hollow cylinder torsional shear tests are widely used for study of cyclic shear response of the sandy soils in the laboratory [12-13]. The cyclic triaxial test though commonly available, is unable to mimic the precise response of soil layers during the earthquake because of its inability to simulate the effects of principal stress rotation which is the important feature of earthquake loading. On the other hand, hollow cylinder torsional apparatus have obtained this ability but, due to its complicated and time consuming saturation process and sample making, the apparatus is not used for practical applications. The simple shear test being less time-consuming and with ability to simulate principal axes rotation can be used for practical purposes. Further, with this apparatus, the constant volume simple shear test can be performed on dry sand, thus, eliminating the saturation procedure. Based upon above facts, simple shear testing apparatus was selected for studying liquefaction potential.

3. SIMPLE SHEAR TEST APPARATUS

In the dynamic simple shear test developed by GDS (Global Digital Systems) Instruments Ltd. UK. as shown in Figs. 2-3, a cylindrical disc shape sample with 70mm diameter and 20mm thickness is placed in the membrane lined, Teflon coated frictionless rings. The steel rings are stiff enough not to permit any lateral displacement during consolidation stage. Hence the soil element will be at zero lateral strain during consolidation and cyclic shearing stages. Undrained cyclic simple shear tests can be performed in true undrained conditions or constant volume conditions. For this study, constant volume cyclic simple shear tests were performed. In the case of constant volume tests, constant volume conditions can be achieved even in the dry soil by constraining sample boundaries (fixing diameter and height). The sample diameter is already constant when it is fixed in Teflon coated rings but the height is fixed by physically clamping the vertical ram. It is impor-tant to note that the decreases or increases of vertical effective stress in the cyclic constant volume test is essentially equal to the increases or decreases of pore pressure when the saturated sample was tested in the true undrained test. In the true undrained test drainage of water is constrained and dissipation of pore does not occur by not allowing the mass of pore water to change [14]. In the constant volume simple shear test, the vertical effective stress decreases or increases when the sample contracts or dilates during cyclic shearing and this increase or decrease in vertical effective stress can be measured from decreasing or increasing reaction on vertical load cell during shearing. In the constant volume test, the vertical effective stress is measured from which pore pressures are determined, while in the true undrained test, the effective vertical stresses are determined from measured pore pressures.

4. LOADING SYSTEM

The GDS simple shear test apparatus consists of vertical and horizontal loading systems. Both vertical and horizontal loading systems are operated by pistons which are controlled by a pneumatic (air) system. The cyclic or monotonic strain controlled loading is applied by constant speed motor. The electro-pneumatic regulator is connected to a data acquisition system and computer, which enables us to apply any form of cyclic loading though, a sinusoidal waveform is generally used, and the magnitude and duration of the waveform can be controlled with GDSLAB software.

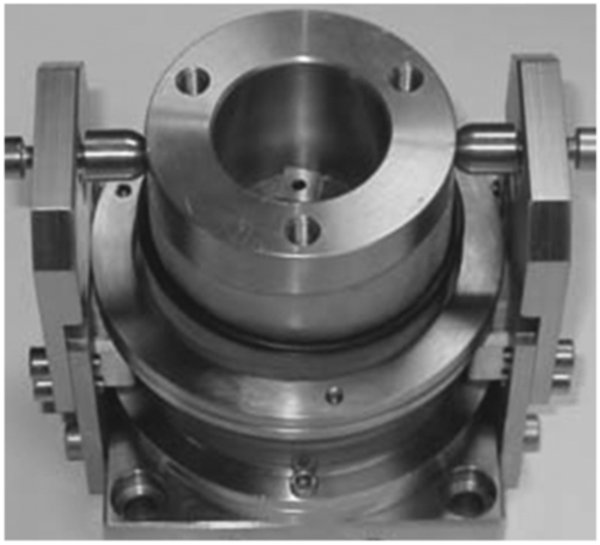

FIG. 2. SAMPLE PREPARATION MOULD

5. DATA ACQUISITION SYSTEM

The high data acquisition and control system is provided with the apparatus. Input channels are used to collect data from two load cells and transducers. Vertical and horizontal large displacement transducers and two LVDTs for measuring small displacements are provided. The high speed data acquisition system is able to collect 100 data points per cycle.

6. MATERIAL TESTED

The soil taken for this study is Leighton Buzzard E-Fraction sand confirming to BS 1881-131 from Sheffield as shown in Table 1. This typically uniform fine silty sand with 85% by weight falling between 90 and 150 micron, is susceptible to liquefaction and has been used for liquefaction studies [15]. The mean diameter (D50mm) is 0.142 with angular shape particles. The maximum and minimum void ratio (emax and emin)) for the sand, determined as per BS 1377, are 1.025 and 0.65 respectively. The specific gravity of the sand is 2.65 determined as per BS 1377.

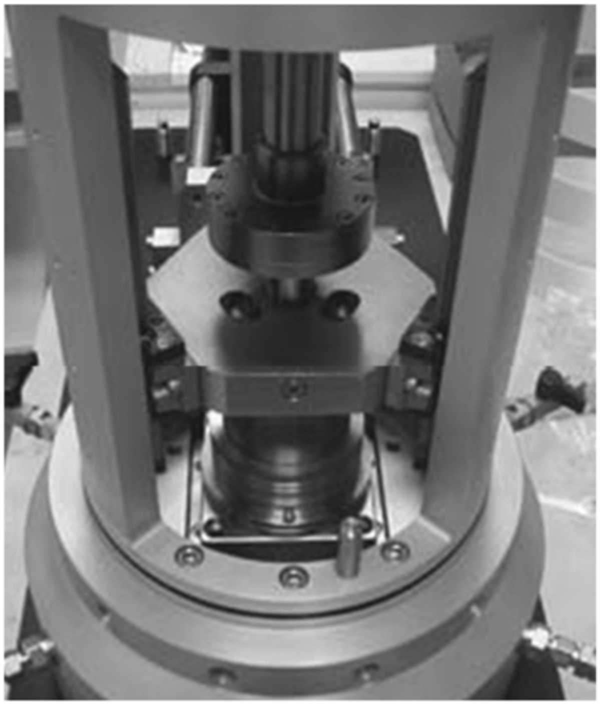

FIG. 3. SIMPLE SHEAR TEST APPARATUS

7. TYPES OF SAMPLES

In this study, two types of samples were prepared. Leighton Buzzard E-Fraction sand was used for the preparation of the samples, therefore, the mineralogical composition of the sand was the same for both types of samples.

7.1 Medium Dense or Type-1 Samples

The sand with initial relative density in the range of 33-66% is usually classified as medium dense sand. This medium dense type or Type-1 samples prepared with target initial relative density of 40% with corresponding void ratio of 0.88 and tested at the initial vertical effective stress of 100 kPa, were the representatives of the soil stiffness and strength at the centre of liquefiable surface foundation soil layer considered in the numerical studies to be performed in the subsequent chapters.

7.2 Dense Sand or Type-2 Samples

The sand with initial relative density in the range of 66-100% is usually classified as dense sand. This dense type or Type-2 samples prepared with initial relative density of 80% with corresponding void ratio of 0.72 and tested at the initial vertical effective stress of 250 kPa, were the representa-tives of the soil stiffness and strength at the centre of non liquefiable base dense soil layer, which is underlying the surface liquefiable layer considered in the numerical model studies.

8. THE SAMPLE FORMATION TECHNIQUE IN LABORATORY

Sand sample at low relative density for simple shear test can be formed by slurry deposition, moist tamping or air pluviation methods [16]. However, dry pluviation method of sample preparation creates a grain structure similar to that of naturally deposited river sands [17] which truly represents the soil deposition in field. In view of these observations, the dry pluviation method was employed in the present study to prepare the soil samples.

TABLE 1. INDEX PROPERTIES OF LB E-FRACTION SAND

Properties	Values
Mean Grain Size D50 mm	0.142
Specific Gravity, Gs	2.65
e_{max}	1.025
e_{min}	0.65

The disc shape specimens of 70mm diameter and 20mm height were prepared by placing the re-quired calculated weight of dry silty sand into the funnel. The funnel was placed at the centre of the bottom of the membrane-lined mould. The funnel was slowly raised along the axis of symmetry of the specimen in such a way that the soil was not allowed any drop height. Uniform tamping with the help of a plunger type tamper was done to achieve the required relative densities. This procedure has been used by researchers to achieve the loosest possible relative densities of less than 10% [18].

Firstly, for air pluviation preparation, a rubber membrane was placed around bottom pedestal and sealed with that bottom pedestal using 'O' ring. Then, the lower base ring was placed on the pedestal and screwed. Next, the upper base ring was placed over the lower base ring and screwed. Then, Teflon coated brass rings were placed over the bottom pedestal. The sample preparation bracket was screwed on the sides of the pedestal. The sample ring keeper was placed on the top of the sample rings. The membrane was stretched around the sample keeper and the sand was poured as discussed above. The top of the sample was leveled so that at least two rings extend above the top of the sample. Another 'O' ring was placed on the top of the sample ring keeper. The top cap was placed at the top of the sample preparation bracket by tightening the screws in such a way that the top cap holders are fixed into the two dimples in sides of the top cap. Before conducting the test, all transducers were set to their zero values. The entire load was applied gently to keep the risk of disturbance to the sample at a minimum.

After completing the sample setup, a vertical confining stress was applied to consolidate the sample up to its target value. Although, consolidation of the sand was instantaneous, samples were consolidated for 30 minutes to ensure complete equilibrium.

After completing consolidation, a vertical loading ram was fixed in position to constrain any vertical displacement by physically clamping the ram in order to achieve constant volume conditions. The value of vertical stress was determined from a vertical load cell reading during the test.

9. RESULTS

9.1 Undrained Cyclic Loading Behaviour of the Medium Dense Sand (Type-1) Samples

A series of strain-controlled cyclic constant volume simple shear tests was performed on medium dense Leighton Buzzard E-Fraction sand prepared with relative density of 40% and tested at ini-tial vertical confining pressure of 100 kPa. The samples were sheared with cyclic constant shear strains at amplitudes of 1, 2 and 5%.

Figs. 4-12 present the stress-strain behaviour, stress path and pore pressure development of medium dense sand Type-1 samples consolidated to vertical effective stress of 100 kPa at initial relative density of 40% and loaded with cyclic constant strain amplitudes of 1, 2 and 5%. The results demonstrate that the sample quickly reaches the state of initial liquefaction when the cyclic pore pressure rapidly rises and for the first time touches the peak value. Due to this rise of pore pressure to peak, the effective stress corresponding to this peak pore pressure touches the zero in 2.8, 1.34 and 0.82 cycles of loading with strain levels of 1, 2 and 5% respectively. This cyclic pore pressure rise to the peak soon becomes stable and constant within few cycles of loading at some point after the moment of initial liquefaction. This point represents the total liquefaction of soil being the characteristic of loose and medium dense sands. Stress-strain and stress path show that the shear stress and stiffness of the soil is completely and permanently lost when the sample totally liquefies after cycles of loading. This characteristic reduction of shear stress (stiffness) at a constant amplitude of shear strain and the rotation of shear stress to strain axis with varying larger amplitude of shear strain results in a reduction of the shear modulus of soil. This type of liquefaction is also known as flow type liquefaction in literature [19] which is the characteristic of loose and medium dense sand. When the sample was strained relatively severally at a larger strain level of 5%, the number of cycles required to reach the initial and the total liquefaction state considerably decreased.

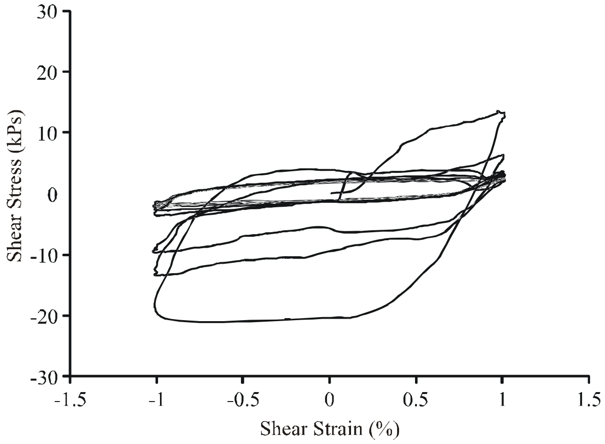

FIG. 4. STRESS-STRAIN BEHAVIOUR FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 1%

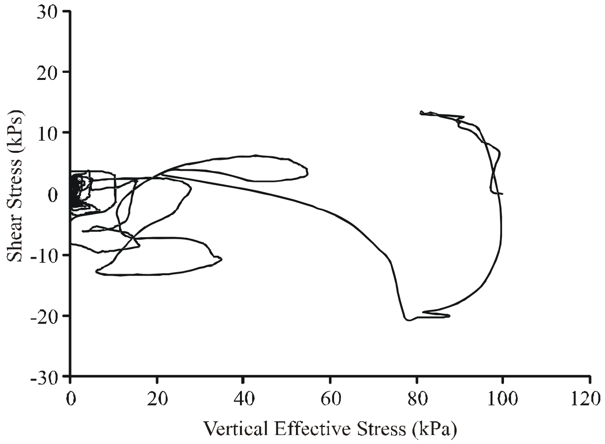

FIG. 5. STRESS PATH FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 1%

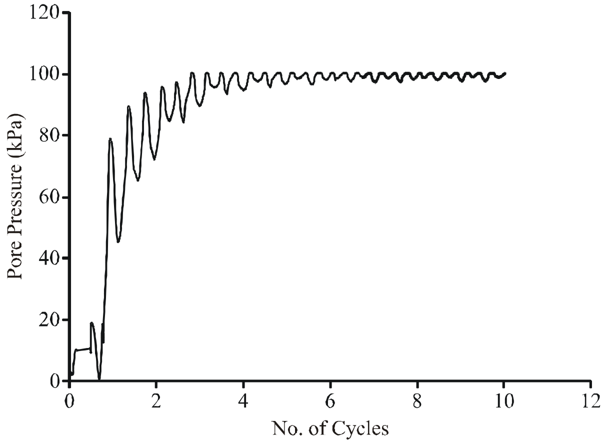

FIG. 6. PORE PRESSURE VS. CYCLES FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 1%

These results demonstrate that as the amplitude of cyclic shear strain increases the number of cycles required to liquefy the medium sand decreases. At a larger shear strain of 5% only a fraction of one cycle is required for the medium

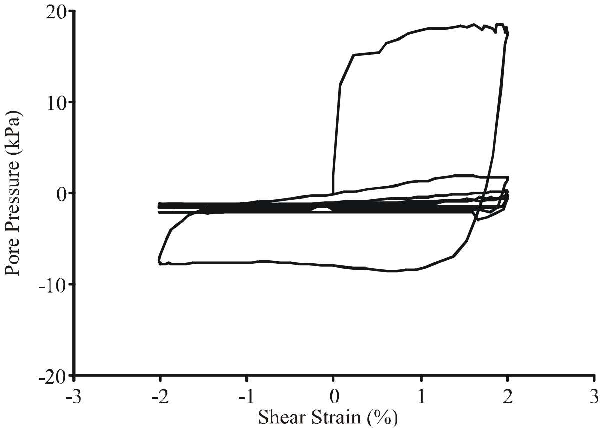

FIG. 7. STRESS-STRAIN BEHAVIOUR FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 2%

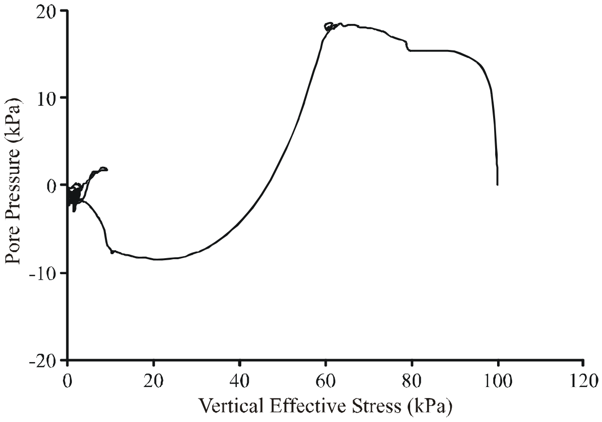

FIG. 8. STRESS PATH FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 2%

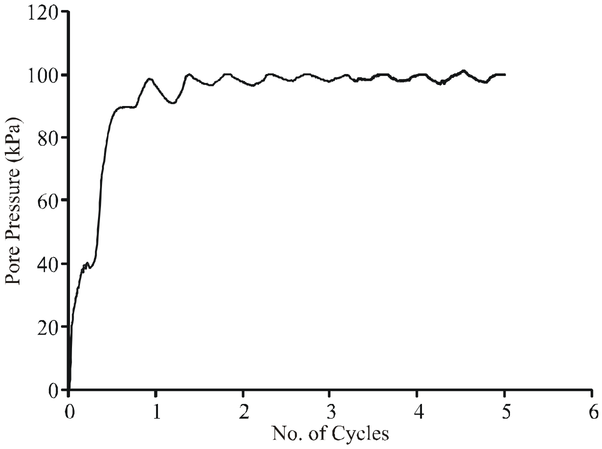

FIG. 9. PORE PRESSURE VS. CYCLES FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 2%

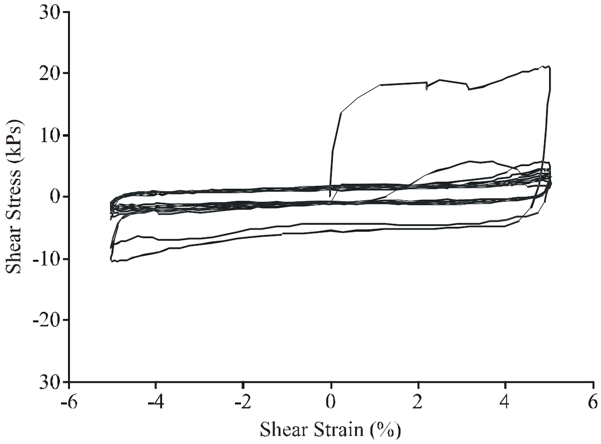

FIG. 10. STRESS-STRAIN BEHAVIOUR FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 5%

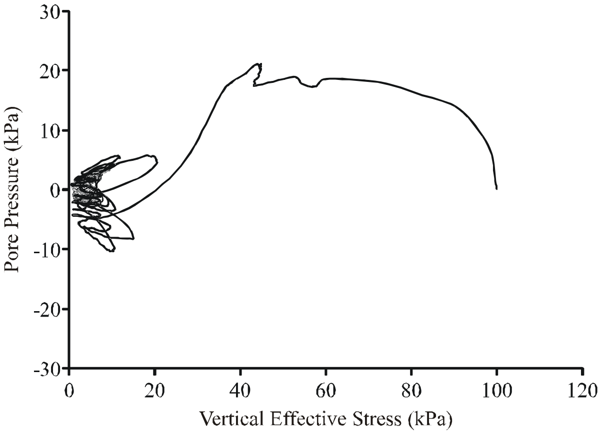

FIG. 11. STRESS PATH FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 5%

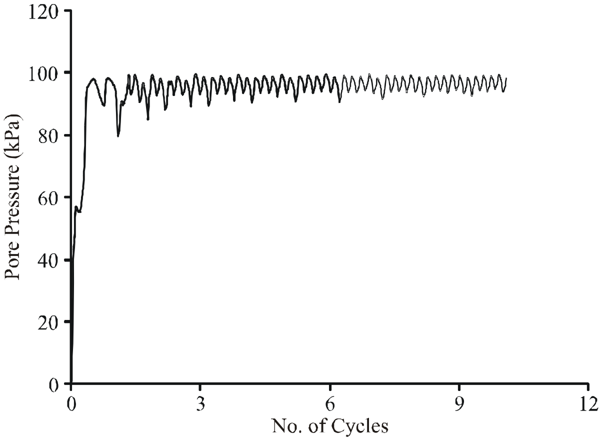

FIG. 12. PORE PRESSURE VS. CYCLES FOR TYPE-1 SAMPLE AT STRAIN AMPLITUDE OF 5%

dense sand to reach the state of initial liquefaction while at a relatively smaller strain level larger number of cycles is required.

9.2 Undrained Cyclic Loading Behaviour of the Dense or Type-2 Samples

In other series, cyclic strain controlled constant volume simple shear tests were performed on dense Leighton Buzzard E-Fraction prepared with a relative density of 80% and tested at the ini-tial vertical confinement pressure of 250 kPa. The samples were sheared with same cyclic constant shear strains amplitudes of 1, 2 and 5%.

Figs. 13-21 present the stress-strain behaviour, stress path and pore pressure development of dense sand Type-2 samples, consolidated to a vertical effective stress of 250 kPa at an initial rela-tive density of 80% and loaded with cyclic constant strain amplitudes of 1, 2 and 5%. The results demonstrate that the dense samples reach the initial liquefaction state after 15, 8.5 and 4.5 cycles of cyclic loading when the cyclic pore pressure gradually increases and for the first time touches the peak values. Due to rise of pore pressure, effective vertical stress corresponding to peak pore pressure gradually touches the zero. After this moment of initial liquefaction, the cyclic pore pressure does not become constant and stable with the number of cycles. Due to which, the sample does not reach the state of total liquefaction characterized by stable and constantly high pore pressures (the effective stress permanently at zero), as opposed to the observed in the case of medium dense sand. The vertical effective stress path and shear strain relationships show that the shear stiffness and strength of the soil decreases in the initial cycles when the sample initially softens with the rise of pore pressure in both loading and unloading phases of a cycle but in the later cycles of cyclic loading the pore pressure and vertical effective stress show cyclic or fluctuating behaviour. This cyclic behaviour of pore pressure and effective stress is related to the dilative behaviour of the sample in loading phase and contractive behaviour in the unloading phase after the phase transformation of dense sand (at which sand shows dilation behaviour instead of contractive before this phase transformation point). This type of behaviour of the dense sand is known as the cyclic mobility of dense sand [19]. Further, there is significant pore pressure development in the unloading phase of cyclic loading as compared to loading in the case of dense sand, as in this case of dense sand early phase transformation occurs. After this phase transformation, the loading phase becomes dilative while unloading still remains contractive. In contrast, in the case of medium dense sand, significant pore pressure develops in both the loading and unloading phases, as in this case no phase transformation occurs or it occurs late.

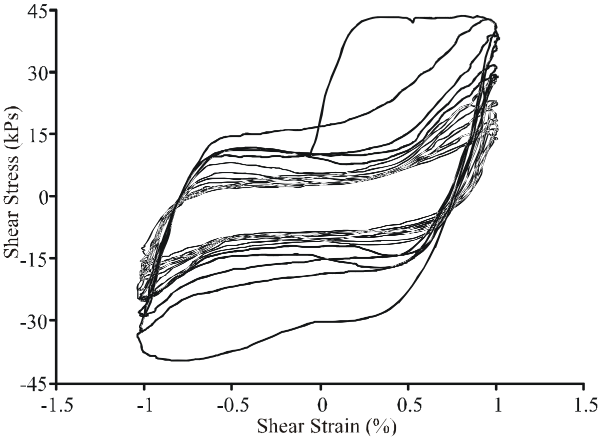

FIG. 13. STRESS-STRAIN BEHAVIOUR OF TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 1%

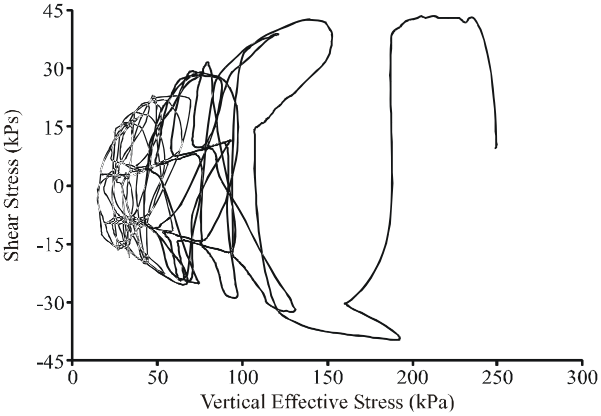

FIG .14. STRESS PATH FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 1%

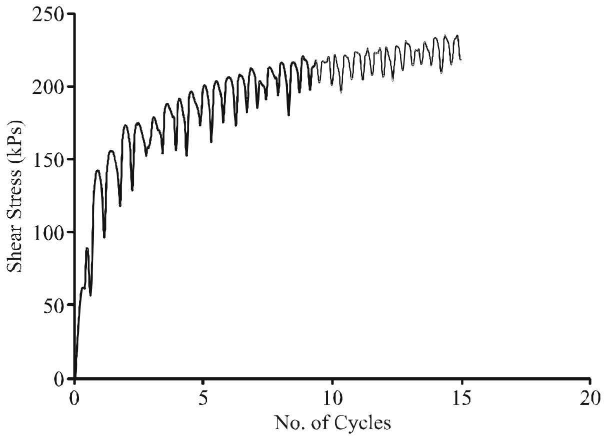

FIG. 15. PORE PRESSURE VERSUS CYCLES FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 1%

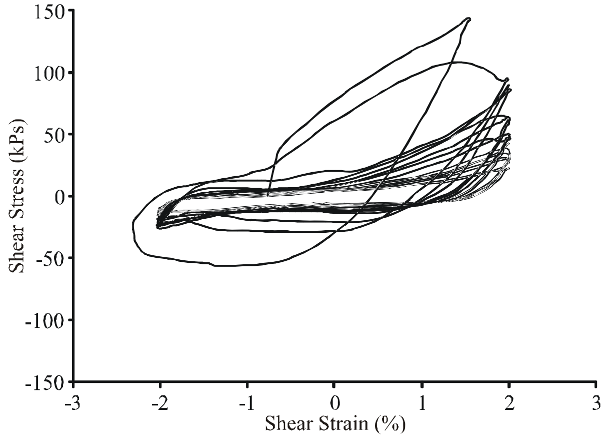

FIG. 16. STRESS-STRAIN BEHAVIOUR OF TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 2%

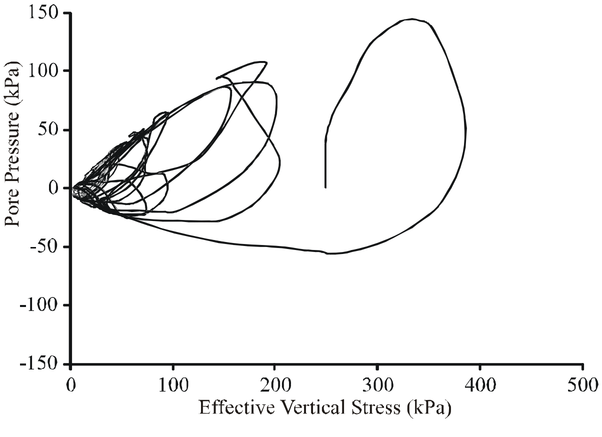

FIG. 17. STRESS PATH FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 2%

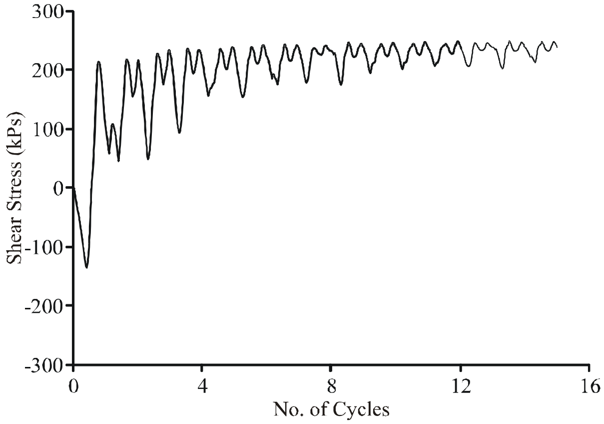

FIG. 18. PORE PRESSURE VERSUS CYCLES FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 2%

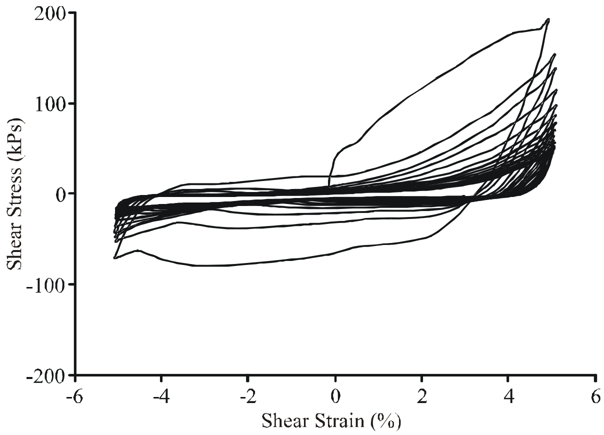

FIG. 19. STRESS-STRAIN BEHAVIOUR FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 5%

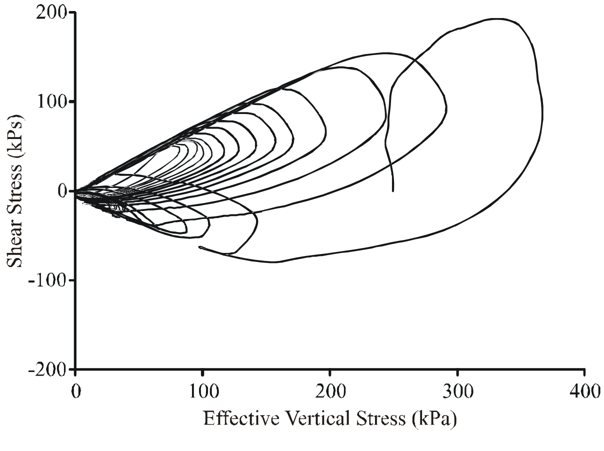

FIG. 20. STRESS-STRAIN BEHAVIOUR FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 5%

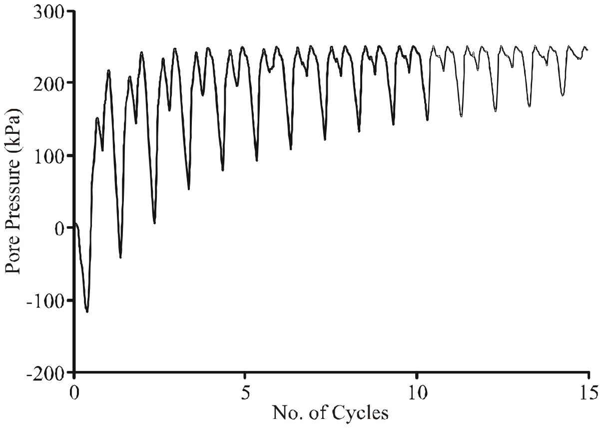

FIG. 21. PORE PRESSURE VERSUS CYCLES FOR TYPE-2 SAMPLE AT STRAIN AMPLITUDE OF 5%

10. CONCLUSIONS

The liquefaction potential of medium dense and dense sand layers was studied by performing constant volume (undrained) cyclic simple shear tests. Based on the results following conclusion can be drawn.

(i) The above results clearly reveal the contrast in the liquefaction behaviour of medium dense and dense sand. Medium dense sand initially liquefies when the cyclic pore pressure touches the peak value for the first time and soon totally liquefies in a few cycles. In contrast, dense sand initially liquefies when the cyclic pore pressure touches the peak value for the first time but does not totally liquefy with cycles of loading due to decreases of pore pressure caused by dilative be-haviour in loading after phase transformation (which occurs early within a few cycles for dense sand). At higher shear strain amplitude of 5%, more pronounced dilation behaviour was observed, though the initial liquefaction reached at smaller number of cycles.

(ii) A medium dense sand surface layer exhibits flow type total liquefaction in cyclic loading in few cycles after initial liquefaction.

(iii) An underlying dense sand base layer shows initial liquefaction in relatively more number of cycles and then cyclic mobility due to which pore pressure increases and decreases with cycles. This cyclic mobility is the characteristics of dense sand.

ACKNOWLEDGEMENTS

The research presented in this paper was carried out as part of Ph.D. (First Author), University of Nottingham, UK. The authors wish to acknowledge the support received from University of Nottingham, UK, and Mehran University of Engineering & Technology, Jamshoro, Pakistan. In addition, the authors are acknowledged the excellent technical support received from the staff of the Nottingham Centre, UK, for Geomechanics.

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